

Structured-groove phase gratings for control and optimization of the spectral efficiency

Johan P. Backlund, Daniel W. Wilson, and Richard E. Muller

*Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Drive, Pasadena, California 91109, USA*

Abstract: Phase gratings are used as dispersers in a variety of imaging spectroscopic instruments. However, conventional phase gratings provide limited spectral range and flexibility to fully optimize instrument performance for challenging applications. Presented here is a new design method that tailors and optimizes the spectral efficiency by introducing an arbitrary structure into the grating groove profile.

©2004 Optical Society of America

OCIS codes: (050.1950) Diffraction gratings, (220.4000) Microstructure fabrication

1. Introduction

In recent years, the demand for high resolution, efficient, fast, and compact imaging spectrometers has indicated that conventional diffraction gratings with pure (saw tooth) blazed profiles offer insufficient flexibility and spectral range to fully optimize the spectroscopic properties of the instrument.

For example, imaging spectrometers operating in the solar reflected spectrum (VNIR+SWIR, 400-2500 nm) require broadband response if the entire range is to be covered with a single grating. Also, the ability to tailor the response permits optimization of the overall system signal-to-noise ratio. The quantum efficiency of silicon detectors typically shows a strong peak towards the middle of the useful wavelength range. If the grating response emphasizes the edges of the spectrum while suppressing the middle, a more balanced overall system response can be obtained [1]. Another spectroscopic instrument that would benefit from a grating with tailored efficiency is the computed-tomography imaging spectrometer (CTIS). A CTIS utilizes a two-dimensional grating to generate multiple spectrally dispersed images without any scanning, and then a tomographic algorithm is used to reconstruct the spectra of all pixels in the scene. The quality of the scene reconstruction would be enhanced by a grating that produced unique spectral variation amongst the 2D orders while maintaining relatively equal illumination of the focal plane array [2].

The research presented here is aimed to fully realize the potential of diffraction gratings that have tailored spectral efficiencies for a given application. By using more advanced grating designs with precisely structured groove shapes, shown in Fig.1, the overall performance of the spectroscopic instruments can be enhanced. In contrast to previous work [2,3], our design method is accurate even for large diffraction angles as long as the scalar electromagnetic theory is applicable. Also, it enables the design and optimization to be carried out at multiple wavelengths simultaneously instead of at one single design wavelength.

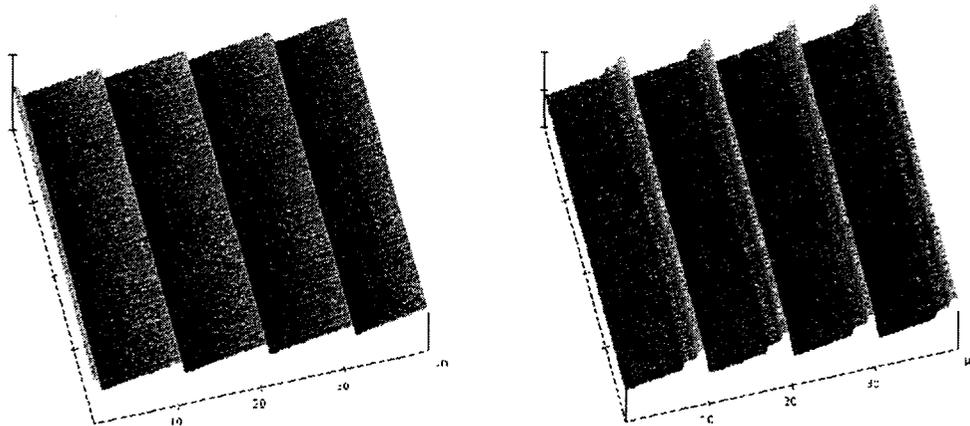


Figure 1. a) An atomic force microscope (AFM) picture of a conventional pure sawtooth blazed grating and b) a structured-groove grating.

2. Design

The design algorithm has been developed based on an existing algorithm “the optimal rotation angle method” (ORA) used to design diffractive optical elements (DOEs) for laser applications [4]. The ORA was originally developed to generate spot patterns at multiple focal distances from the DOE plane and with simultaneous focusing of different wavelengths by the same DOE. The design algorithm presented here uses the same optimization scheme and thus take advantage of the accuracy and flexibility typical for the ORA method. But instead of optimizing focused spot patterns in real space the algorithm optimizes spatial frequency components within the frequency domain at multiple wavelengths.

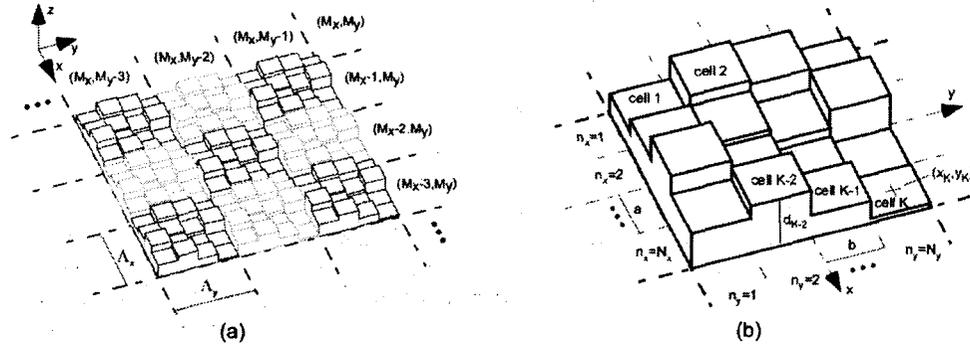


Figure 2. a) A 3-by-3 grating period section where each period b has been sampled into (N_x, N_y) cells.

Figure 2a shows a schematic picture of a general two-dimensional grating that has been drawn as a checkerboard only for clarity and where each grating period has been divided into cells as shown in Fig. 2b. It can be shown that to obtain the diffraction order efficiency from an entire grating only the normalized field from one single grating period needs to be calculated. From here on only one grating period is considered.

The design algorithm is iterative and starts by calculating the field contribution from each single cell to each target spatial frequency, defined by a diffraction order and wavelength. The cell height, d_k , is set to a random value initially. The efficiency from one grating period is then obtained by summing over all cell contributions. Based on the newly calculated field values in the targets one cell height at the time is then optimized using the ORA scheme. When all cells have been optimized, the efficiencies of all orders are recalculated based on the new cell height values and weights are adjusted. A new iteration starts by optimizing each cell and the iteration continues until the uniformity error between the actual and the desired efficiencies in the target frequencies are within acceptable levels or the improvement stagnates.

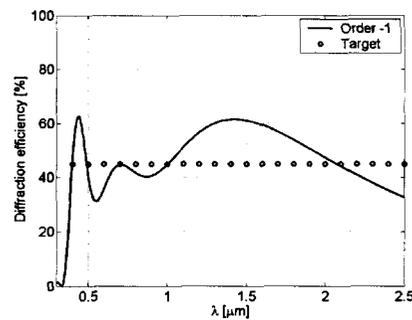


Figure 3. The design targets indicated by circles define the desired spectral response and the solid curve the actual efficiency response in order $n=-1$ for the designed grating.

Now, how do we specify to the design algorithm the desired functionality? Shown in Fig.3 is a number of targets (circles) placed along the spectrum to sample a desired efficiency response for order, $n = -1$. The design algorithm tried to bring efficiency into these targets as close to the design specification as possible without losing total efficiency. The spacing between the targets was chosen to ensure continuous and smooth efficiency. The match is not perfect but it is optimized however, and trying to get a more uniform efficiency response would result in considerable total efficiency loss.

3. Fabrication and Experiments

A fused silica substrate was spin-coated with PMMA and then baked. The gratings patterns were prepared and E-beam exposed using a JEOL JBX 9300FS E-beam system and then developed in acetone [5]. In the case of a reflective grating, a 600Å reflective layer of aluminum was thermally evaporated. Two different grating examples are presented below.

I. Reflection one-dimensional grating for 380-2500nm wavelength.

This grating was designed to provide continuous efficiency over the entire solar black body radiation spectrum 380-2500nm. The grating period was $\Lambda = 10\mu\text{m}$ divided into $N=100$ cells. The desired spectral response for the -1 order (defined by targets) is shown in Fig.3 in the previous section. The resulting simulated efficiency is also shown (solid curve). An AFM picture of the fabricated grating is presented in Fig. 1b. Shown is Fig 4a. is the experimental result compared to vectorial simulations and the scalar counterpart. Notice, that the curves has been blue-shifted slightly compared to Fig 2 to match the insufficient development (92%).

II. Transmission two-dimensional grating for 400-1500nm wavelength.

This two-dimensional transmission grating was designed to separate the efficiency peaks for four different orders by approximately 200nm. The grating period was $(\Lambda_x, \Lambda_y) = 10\mu\text{m}$ divided into $(N_x, N_y = 40)$ cells. Shown in Fig.4b is the experimental result compared to scalar simulations. The figure caption shows an AFM-picture of the fabricated grating.

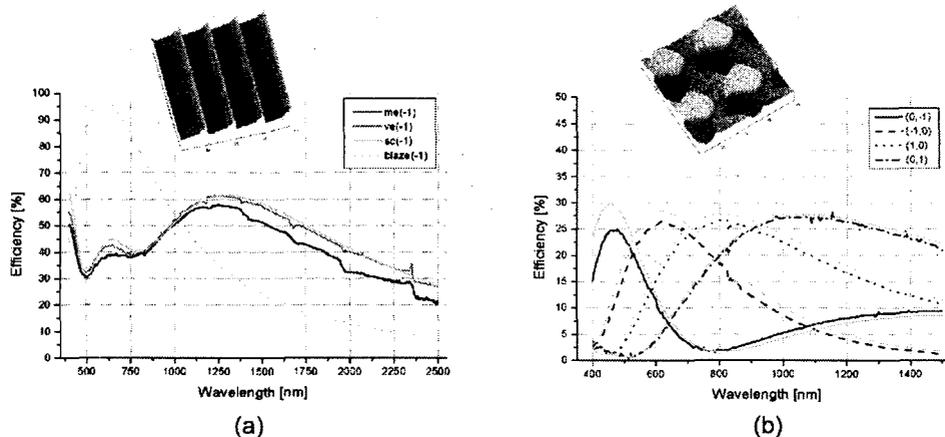


Figure 4. a) 1-D grating; Measured efficiency (black), vectorial simulation (gray), and scalar simulation (light gray). The dashed curve shows for comparison the simulated efficiency for a pure blazed grating. b) 2-D grating; Measured efficiency (black) and scalar simulation (light gray). The inset in both a) and b) is an AFM-picture of each fabricated grating.

4. Summary

Structured-groove gratings can be used to tailor and optimize the spectral dispersion for demanding applications. The sophisticated grating groove structure provides flexibility. However, the high precision patterning requires e-beam but can be replicated by modern techniques such as nano-imprint.

5. References

- [1] P. Z. Mouroulis, D. W. Wilson, P. D. Maker, and R. E. Muller, "Convex grating types for concentric imaging spectrometers", *Appl. Opt.*, Vol. 37, No. 31, 7200-7208 (1998).
- [2] J. F. Scholl, E. L. Dereniak, M. R. Descour, C. P. Tebow, and C. E. Volin, "Phase grating design for a dual-band snapshot imaging spectrometer", *Appl. Opt.*, Vol. 42, No. 1, 18-29 (2003).
- [3] B.-Z. Dong, G.-Q. Zhang, G.-Z. Yang, B.-Y. Yuan, S.-H. Zheng, D.-H. Li, et al., "Design and fabrication of a diffractive phase element for wavelength demultiplexing and spatial focusing simultaneously", *Appl. Opt.*, Vol. 35, No. 35, 6859-6864 (1996).
- [4] J. Bengtsson, "Design of fan-out kinoforms in the entire scalar diffraction regime with an optimal-rotation-angle method", *Appl. Opt.*, Vol. 36, No. 32, 8453-8444 (1997).
- [5] D. W. Wilson, P. D. Maker, R. E. Muller, P. Mouroulis, and J. Backlund, "Recent advances in blazed grating fabrication by electron-beam lithography", in *Current Developments in Lens Design and Optical Engineering IV*, P. Mouroulis, W. J. Smith, and R. B. Johnson Eds., SPIE Proc. 5173, 115-126 (2003).